

High Energy Density Regenerative Fuel Cell Systems for Terrestrial Applications

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ABSTRACT

Regenerative Fuel Cell System (RFCS) technology for energy storage has been a NASA power system concept for many years. Compared to battery-based energy storage systems, RFCS has received relatively little attention or resources for development because the energy density and electrical efficiency were not sufficiently attractive relative to advanced battery systems. Even today, RFCS remains at a very low technology readiness level (TRL of about 2 indicating feasibility has been demonstrated). Commercial development of the Proton Exchange Membrane (PEM) fuel cells for automobiles and other terrestrial applications and improvements in lightweight pressure vessel design to reduce weight and improve performance make possible a high energy density RFCS energy storage system. The results from this study of a lightweight RFCS energy storage system for a remotely piloted, solar-powered, high altitude aircraft indicate an energy density up to 790 w-h/kg with electrical efficiency of 53.4% is attainable. Such an energy storage system would allow a solar-powered aircraft to carry hundreds of kilograms of payload and remain in flight indefinitely for use in atmospheric research, earth observation, resource mapping, and telecommunications. Future developments in the areas of hydrogen and oxygen storage, pressure vessel design, higher temperature and higher-pressure fuel cell operation, unitized regenerative fuel cells, and commercial development of fuel cell technology will improve both the energy density and electrical efficiency of the RFCS.

INTRODUCTION

NASA has for some time recognized the potential for a RFCS to store large amounts of energy for space applications where energy production is cyclic, as is the case for solar energy power generation. NASA's familiarity with fuel cell primary power led to NASA's recognition of the viability of coupling the fuel cell with an electrolyzer and a means of storing oxygen and hydrogen to form a secondary "battery" energy storage system. The Unitized Regenerative Fuel Cell (URFC) refines this concept by using the same cell electrodes to perform both the electrolyzer function (equivalent to battery charging) and the fuel cell function (equivalent to battery

discharging). A Unitized Regenerative Fuel Cell System (URFCS) incorporates the URFC into an overall energy storage system.

Solar power system studies for orbiting platforms, Mars and Moon bases have included a RFCS to store energy from the sun. Although batteries have higher round trip energy efficiencies, the RFCS or URFCS has several key characteristics that make it an attractive energy storage alternative for space applications. The most significant of these is the potential ability to store large amounts of energy in a low mass package. This characteristic makes it similarly attractive for terrestrial use in applications involving high energy and low mass such as rechargeable electric vehicles, portable power systems and solar airplanes. Specific energy or energy density is a parameter that describes how much energy can be delivered from an energy storage system per unit mass of that energy storage system. A typical unit for energy density is watt-hours per kilogram of mass (w-h/kg). The URFCS, by virtue of its single cell stack, intuitively seems the most likely RFCS to achieve the lowest mass for a given output energy, provided the electrochemical performance is similar to that provided by discrete electrolyzer and fuel cell stacks. In order to achieve this high energy density, a clear understanding of the system parameters that most effect energy density is needed. In addition, an innovative URFCS system design is needed that also minimizes the weight of components other than the URFC stack.

URFCS ENERGY DENSITY

The URFCS energy density is theoretically very high. The energy density is calculated as the amount of energy output during discharge divided by the total weight of the URFCS. The output energy of the URFCS is expressed as

$$\text{Output Energy} = nV_d I_d t_d \quad (1)$$

where V_d = discharge cell voltage, volts
 I_d = average discharge current, amps
 n = number of cells in the URFC stack
 t_d = discharge time, hours

If all the weight other than the reactants is zero, the energy density would theoretically be expressed as

$$\text{Energy Density} = \frac{\text{Output Energy}}{\text{Reactant Weight}} = \frac{nV_d I_d t_d}{M_w} \quad (2)$$

where M_w = mass (kg) of the hydrogen and oxygen that have reacted to form water. However, from Faraday's Law,

$$\frac{nI_d t_d}{M_w} = \frac{2976.2 \text{ cell-amp-hr}}{\text{kg H}_2\text{O}} \quad (3)$$

Substituting this into equation 2, the theoretical maximum energy density at any discharge voltage is then expressed as

$$\text{Energy Density} = \frac{2976.2 V_d \text{ watt-hr}}{\text{kg H}_2\text{O}} \quad (4)$$

At an ideal reversible cell voltage of 1.23 volts, the theoretical energy density is 3,660 watt-hr/kg, which is several times larger than the theoretical energy density of currently known battery systems. [1] For a practical system, the weight of the URFCs includes weight other than the reactants themselves. The energy density of a practical system is calculated by the equation

$$\text{Energy Density} = \frac{\text{Output Energy}}{\text{Total Weight}} = \frac{2976.2 V_d M_w \text{ watt-hr}}{M_w + \text{Other Weight, kg}} \quad (5)$$

The other URFCs weight includes oxygen and hydrogen storage tank weight, URFC stack weight, water storage tank weight, and ancillary weight. If these are substituted into equation 5,

$$\text{Energy Density} = \frac{2976.2 V_d \text{ watt-hr/kg}}{1 + \frac{T_w}{M_w} + \frac{S_w}{M_w} + \frac{W_w}{M_w} + \frac{A_w}{M_w}} \quad (6)$$

where T_w = Dry Weight of Gas Storage Tanks, kg
 S_w = Dry Weight of URFC Stack, kg
 W_w = Dry Weight of Water Storage Tank, kg
 A_w = Dry Weight of URFCs Ancillaries, kg

TANK WEIGHT Tank weight is a function of both the pressure and volume of the tank. Figures-of-Merit for lightweight gas storage tanks are calculated as,

$$\text{Figure-of-Merit, cm} = \frac{\text{Pressure, kg/cm}^2 * \text{Volume, cm}^3}{\text{Tank Weight, kg}} \quad (7)$$

The Figure-of-Merit for a current state-of-the-art lightweight tank is approximately 4.0×10^6 cm. [1] A design safety factor of 1.5 was chosen for the tank design. Also, a 5% level of unused reactant was assumed for the tank. Using this figure-of-merit, safety factor, and level of unused reactant, the mass of the reactant tanks are

$$\text{H}_2 \text{ Tank, kg} = \frac{(1.5 \text{MOP})(V, \text{cm}^3)}{4.0 \times 10^6 \text{ cm}} = \frac{1.5 * 1.05 (\text{gmole H}_2) RT}{4.0 \times 10^6 \text{ cm}} \quad (8)$$

$$\text{O}_2 \text{ Tank, kg} = \frac{(1.5 \text{MOP}_G)(V, \text{cm}^3)}{4.0 \times 10^6 \text{ cm}} = \frac{1.5 * 1.05 (\text{gmole O}_2) RT}{4.0 \times 10^6 \text{ cm}} \quad (9)$$

where MOP_G = Maximum Operating Gas Pressure, kg/cm²

$$R = \frac{84.78 \text{ kg-cm}^3}{\text{cm}^2 \text{-gmole-K}}$$

T = Temperature, K

gmole O_2 = gram moles of oxygen reacted

gmole H_2 = gram moles of hydrogen reacted

The total dry mass of the tanks is then

$$T_w = \frac{1.5 * 1.05 (\text{gmole O}_2 + \text{gmole H}_2) RT}{4.0 \times 10^6} \quad (10)$$

Correlating this to the moles of water produced during discharge yields

$$T_w = \frac{1.5 * 1.05 (1.5 \text{gmole H}_2\text{O}) RT}{4.0 \times 10^6} \quad (11)$$

$$T_w = \frac{1.5 * 1.05 * 1.5 (1000 M_w / 18) RT}{4.0 \times 10^6}$$

Therefore the term T_w/M_w in Equation 6

$$\frac{T_w}{M_w} = 3.28 \times 10^{-5} RT \quad (12)$$

STACK WEIGHT The cell stack weight has a strong correlation to the power level generated by the cell stack. Both the size of the cells and the number of cells are generally proportional to the power level of the cell stack. Therefore the URFC stack weight can be expressed as

$$S_w = \frac{\text{Stack Power, watts}}{\text{Power Density, watt/kg}} \quad (13)$$

Substituting for the stack power,

$$S_w = \frac{n V_d I_d \text{ watt}}{\text{Power Density, w/kg}} \quad (14)$$

Multiplying both the numerator and denominator by the discharge time, t_d , yields

$$S_w = \frac{n V_d I_d t_d \text{ w-hr}}{t_d \text{ Power Density, w-hr/kg}} \quad (15)$$

Therefore,

$$S_w = \frac{2976.2 V_d \text{ cell-A-hr/kg} * (M_w \text{ kg})}{t_d \text{ Power Density, w-hr/kg}} \quad (16)$$

Dividing each side by M_w , the stack weight term in equation 6 can be written

$$\frac{S_w}{M_w} = \frac{2976.2 V_d}{t_d \text{ Power Density}} \quad (17)$$

The power density of a particular manufacturer's URFS cell stack is itself a function of the discharge cell voltage, V_d .

$$\text{Power Density} = \frac{\text{Output Power}}{S_w} = \frac{nV_d i_d A_c \text{ cm}^2}{S_w} \quad (18)$$

$$\text{Power Density} = \frac{V_d i_d A_t}{S_w} \quad (19)$$

where

i_d = Discharge current density, A/cm²

A_c = Unit Cell Area, cm²

A_t = Total Cell Area, cm²

The cell current density can be expressed as a function of the discharge cell voltage, V_d , based on the discharge cell voltage versus current density curve for the URFC.

$$i_d = f(V_d) \quad (20)$$

The ratio of the total cell area to stack weight was estimated as a constant for the purposes of this paper. If the endplate weight is more than 10% of the overall stack weight, then the stack weight should be estimated on the basis of a per cell weight plus the endplate weight.

$$\frac{A_t}{S_w} = K_a \quad (21)$$

Substituting Equations 12,20 and 21 into the energy density equation 6, yields

$$\text{Energy Density} = \frac{2976.2 V_d}{1 + 3.28 \times 10^{-5} RT + \frac{2976.2}{K_a t_d f(V_d)} + \frac{W_w}{M_w} + \frac{A_w}{M_w}} \quad (22)$$

WATER STORAGE TANK WEIGHT The water storage tank weight is estimated to be proportional to the volume and pressure of the stored water. Similar to the gas tanks, a design safety factor of 1.5 was used. A factor of 1.14 was used to account for the water tank being sized to accommodate a 14% surplus of water. The figure-of-merit used in this analysis is

$$K_w = 0.33 \times 10^6 \text{ cm} = \frac{1.5 \text{ MOP}_w V_w}{W_w} \quad (23)$$

where,

V_w = Volume of water stored, cm³

MOP_w = Max. Operating Pressure of water stored, kg/cm²

Because water is relatively incompressible, the volume of water is proportional to the mass of the water. Therefore,

$$V_w = \frac{1.14 M_w}{\rho} \quad (24)$$

where

$\rho = .001 \text{ kg/cm}^3$ (the density of water)

Therefore,

$$\frac{W_w}{M_w} = \frac{1.5 * 1.14 \text{ MOP}_w}{\rho K_w} = \frac{1710 \text{ MOP}_w}{K_w} \quad (25)$$

ANCILLARY WEIGHT For the purposes of this paper, ancillary weight was established at 67.9% of the reactant

weight. This percentage was based on the analysis of the URFC ancillary weight described later in this paper. Therefore,

$$\frac{A_w}{M_w} = 0.679 \quad (26)$$

Substituting Equations 25 and 26 into the energy density equation 22 yields

$$\text{Energy Density} = \frac{2976.2 V_d}{1 + 3.28 \times 10^{-5} RT + \frac{2976.2}{K_a t_d f(V_d)} + \frac{1710 \text{ MOP}_w}{K_w} + 0.679} \quad (27)$$

Following are a few observations of equation 27,

1) Ideally, the storage temperature of the tanks should be as low as possible because the gaseous reactants are denser at low temperature. This allows smaller tanks (ie. lighter tanks) to be used.

2) The output voltage of the URFC is a strong determinant of the overall energy density, and should be optimized for minimum weight of the URFC. The optimum output voltage per cell is influenced not only by the E vs I curve of the cell, but also by other system weight terms, which should be taken into account.

3) Longer discharge times increase the energy density.

DISCHARGE VOLTAGE AND CURRENT DENSITY OPTIMIZATION Some representative values of T , K_a , t_d , MOP_w and $f(V_d)$ were chosen and parametric graphs were plotted of energy density versus V_d . Figure 1 shows the effect of discharge time on the energy density of the URFC. Longer discharge times result in higher energy densities. This is because for a given energy capacity, a short discharge time results in a high power rating which requires a larger cell stack. For a given discharge time, the energy density also increases as the power level from each cell increases, because fewer cells are needed. As the power level from each cell increases, the discharge voltage decreases.

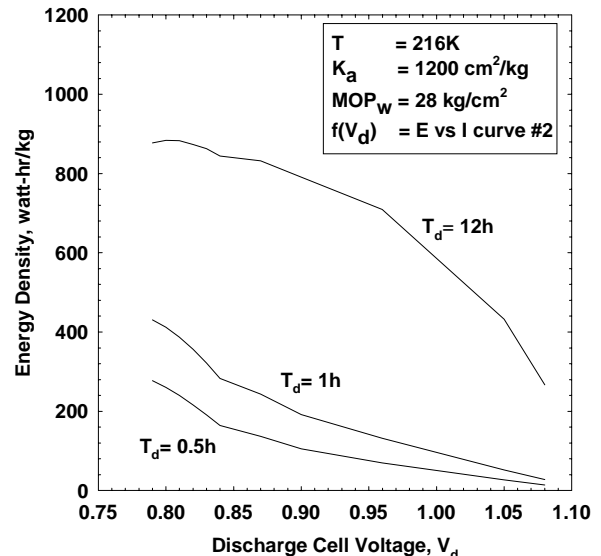


Figure 1. Effect of T_d on Energy Density

Figure 2 shows how for a given discharge time, the energy density varies for changes in cell voltage performance. In Figure 2, the two plots show the effect of the E vs. I curves (shown in Figure 3) on the energy density. As expected, better cell voltage performance results in increased energy density.

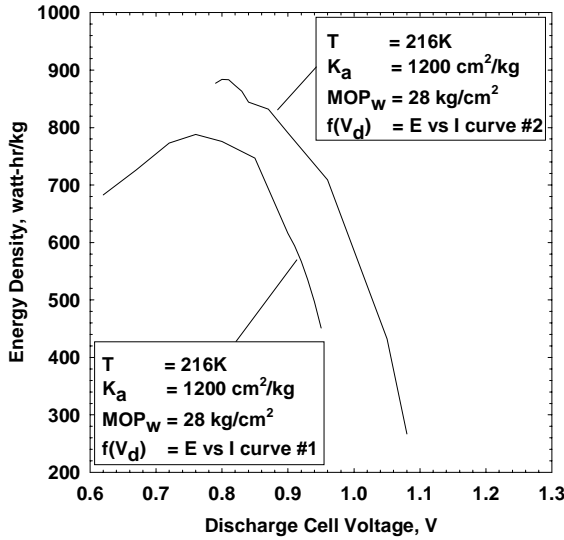


Figure 2. Effect of $f(V_d)$ on Energy Density

The difference in the energy density between the two curves in Figure 2 is on the order of up to 50%, while for different discharge times, the difference in energy density can be as high as a factor of 10.

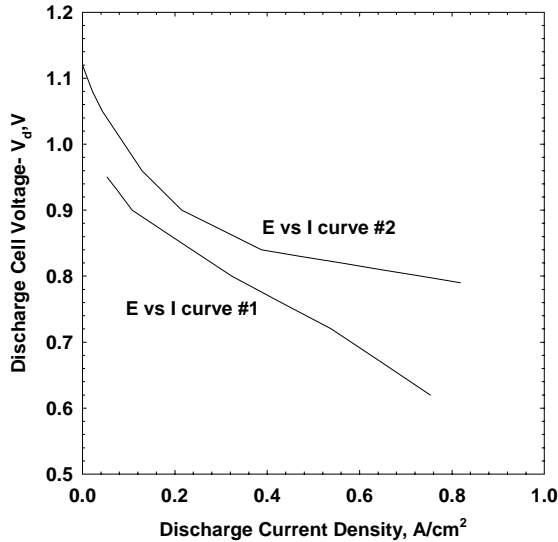


Figure 3. Discharge Voltage vs. Current Density

URFCS EFFICIENCY The energy efficiency of a regenerative fuel cell system relates the relative amounts of energy needed to charge and discharge the system. The amount of reactants used during charging must be the same as that used during discharging. Therefore,

$$n_c I_c t_c = n_d I_d t_d \quad (28)$$

where n_d = number of cells used during discharge
 n_c = number of cells used during charge
 I_c = average charging current, A
 t_c = charge time, hr

The energy efficiency is then written as

$$\eta = \frac{\text{Output Energy}}{\text{Input Energy}} = \frac{V_d n_d I_d t_d}{V_c n_c I_c t_c} = \frac{V_d}{V_c} \quad (29)$$

Figure 4 adds the efficiency relationship to the data plotted in Figure 2 to create a nomograph illustrating the relationships between energy density, energy efficiency, discharge voltage, and charge voltage.

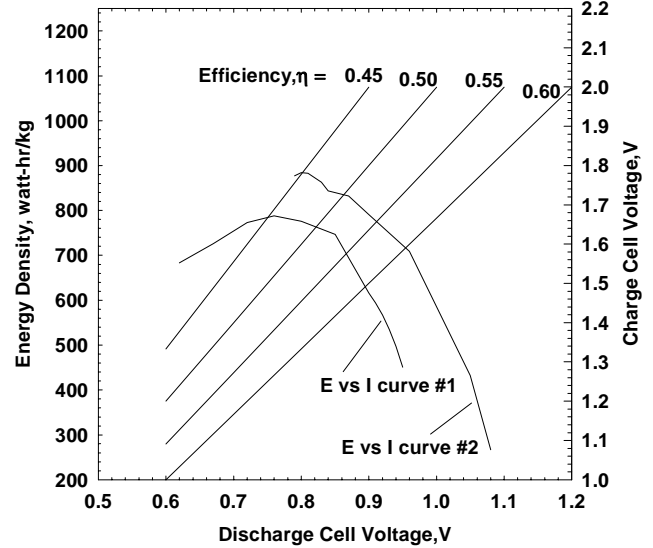


Figure 4. Effect of Efficiency on Energy Density

and charge voltage. Figure 4 shows that as the discharge voltage is decreased, the energy density increases as the energy efficiency decreases. The decrease in energy efficiency will have the effect of increasing the size (weight) of the power generation device (ie. solar array, wind turbine, etc.), so that as the energy storage system gets lighter, the energy generating device gets heavier. The overall weight optimization must therefore take this effect into account.

URFC APPLICATIONS AND THE SOLAR AIRPLANE

There are several applications for which a URFCS would be an effective energy storage system. Among these applications are Lunar/Mars surface power, high altitude balloons, high altitude solar airplanes and rechargeable cars. Only the solar airplane application is treated in this paper. Previous papers [1],[2] have discussed regenerative fuel cells for solar airplanes. The solar airplane is an ultralight flying wing aircraft where the top surface of the wing is covered with solar cells that produce electric power to run propeller motors during the day. To date, these planes have been forced to glide back to earth at night because there is no energy storage system aboard to provide power to the motors at night. A regenerative fuel cell energy storage system would produce reactants via electrolysis during the day using solar array power, and at night use those reactants in a fuel cell to produce power to maintain the solar airplane in flight. This arrangement would allow the solar airplane to remain aloft indefinitely. A picture of the Centurion solar airplane built by AeroVironment, Inc is shown during flight in figure 5.

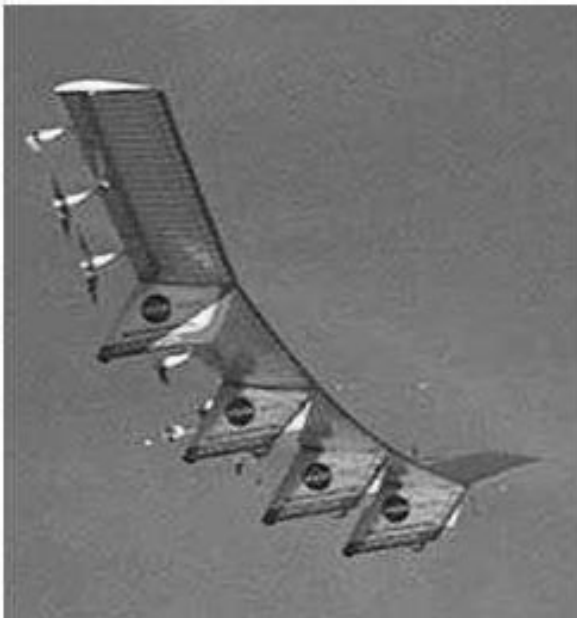


Figure 5. Centurion Solar Powered Aircraft

Typically these kinds of airplanes are expected to fly above 15,240m (50,000ft), which is above the jet stream. At this altitude, the ambient atmosphere is quite cold and at low pressure. Figures 6 and 7 indicate the relationships of temperature and pressure as a function of altitude that were used to model the environment of the URFCS for the solar airplane.

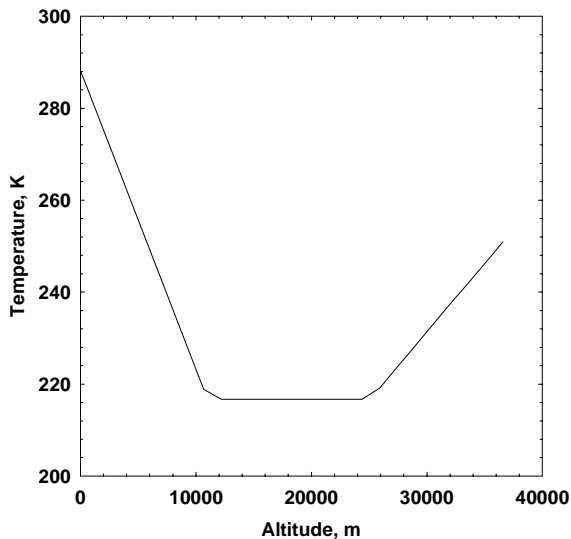


Figure 6. Ambient Temperature

The charge/discharge cycle is approximately 12hr/12hr, depending on the latitude and the time of year. A typical power profile is shown in figure 7. The DC power profile during the 12-hour charge period is sinusoidal. The power profile is essentially constant over the 12-hour discharge period. By integrating the charging power over the charging period to get the charging energy and calculating the required discharge energy, the overall electrical efficiency required by the plane is approximately 53.4%. The most challenging requirement of the solar airplane is the need to be extremely lightweight. The energy storage system for the solar-powered airplane has been projected to require an energy density of 400 w-hr/kg or

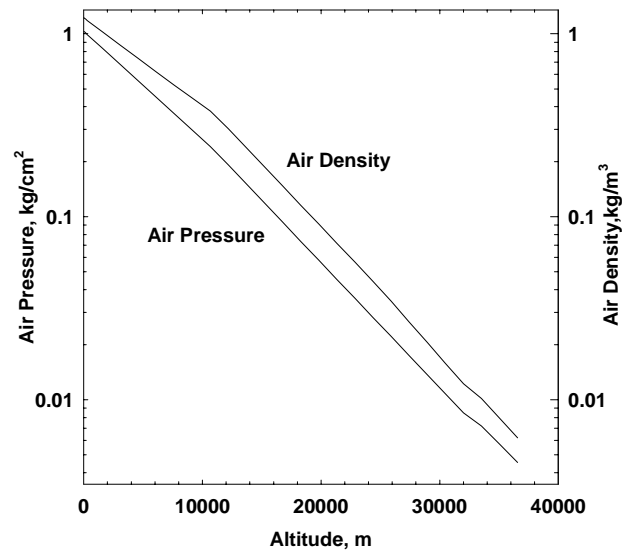


Figure 7. Ambient Air Pressure and Density

greater. The RFCS energy storage system is the only viable energy storage system candidate potentially capable of meeting this stringent weight restriction. A conceptual design of an ultra-lightweight URFCS was created in order to analyze its mass and performance for the solar airplane.

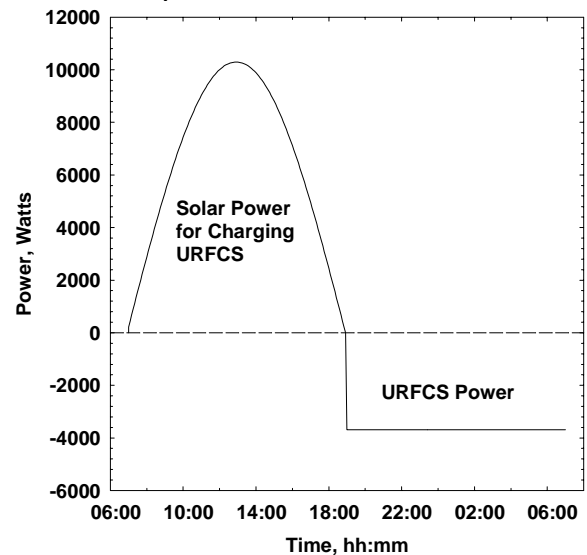


Figure 7. Power Profile of the Solar Airplane

The schematic for the URFCS showing the major components located within a protective shell is shown in figure 8.

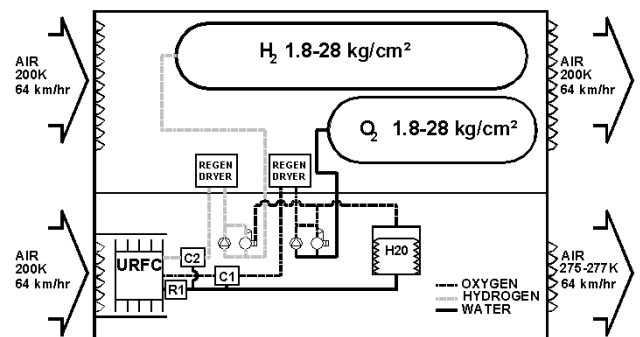


Figure 8. URFCS Schematic

URFC ENERGY STORAGE SYSTEM COMPONENT DESCRIPTION

URFC STACK The energy storage system analyzed in this paper uses a Unitized Regenerative Fuel Cell in the cell stack. A cell of this type is being developed under a NASA SBIR contract [3]. The cell consists of a Proton Exchange Membrane (PEM) electrode assembly separating the two gas compartments. During electrolysis, water vapor is fed to the electrodes from a third and separate water compartment. Water is evaporated from the water compartment within the URFC stack and diffuses to the electrolysis reaction sites. As water vapor is electrolyzed at the electrode surface, a vapor diffusion gradient is created which provides the driving force for continued evaporation from the water compartment. During fuel cell operation, the oxygen and hydrogen reactants are not circulated throughout the URFC stack but are fed passively to the cell stack. The product water is removed passively because of a pressure differential between the cell stack gas compartments and the cell stack water compartment. The pressure of the gases is always greater than the pressure of the water, so liquid water is not free inside the gas compartments but is retained inside the water compartment. This cell is an air-cooled cell, but if desired could be made liquid-cooled.

GAS STORAGE TANKS The gas storage tanks are ultra-lightweight composite wrapped tanks of the type developed for NASA and DOE [1]. The peak operating pressure is 28 kg/cm² (400 psia), with a factor of safety of 1.5 and a performance figure-of-merit of approximately 4.0×10^6 cm (1.5x10⁶ in.). The tanks are uninsulated and exposed to the cold ambient atmospheric environment. The dewpoint of the stored gas is the same as or colder than the outside ambient air temperature, so there is no condensation or freezing of water inside the tank.

WATER TANK The water reservoir is a bellows tank. The bellows is designed such that the spring force to expand the bellows to its resting length produces a suction pressure on the water side of the tank. This suction keeps the pressure of the water in the URFC stack less than the gas pressure at all times. The bellows expands or contracts depending on the water volume. The tank is pressure referenced to the oxygen pressure of the URFC stack.

CONDENSERS The condensers remove most of the water vapor from the product gas streams during electrolysis operation. The condensing temperature is slightly above freezing (4C). The condensed water is sucked up by a porous frit-condensing surface, which provides gas/liquid separation, and returns to the URFC stack to be electrolyzed. The water, which is saturated with dissolved oxygen and hydrogen, is passed through a catalyst bed to recombine the dissolved gases. During fuel cell operation, these condensers act as humidifiers by humidifying the incoming dry gases.

REGENERATIVE DRYERS Each dryer condenses (or freezes) the water vapor out of the product gas streams and lowers the dewpoint of the gas stored in the tanks to the ambient temperature. The water is kept within the dryer until NASA/TM—1999-209429

the URFC stack is operated as a fuel cell. When this occurs, the water inside each dryer is warmed and rehumidifies the gas entering the fuel cell. The available cold ambient environment provides the cooling, and fuel cell waste heat or separate heaters supply the heating.

GAS REGULATORS/ CHECK VALVES The regulators regulate the pressure from the storage tanks down to the operating pressure of the fuel cell. The check valves prevent the gas from the storage tanks from bypassing the pressure regulators.

ENERGY STORAGE SYSTEM SHELL The supporting structure around the URFC stack is an aerodynamic shell that controls the amount of cooling air that passes over the URFC stack. The shell also maintains a flow of cold air over the regenerative dryers and gas storage tanks. Within the shell is a separate compartment that uses the air heated by the URFC stack to maintain the balance of the liquid water handling components above freezing.

URFC ENERGY STORAGE SYSTEM OPERATION DESCRIPTION

ELECTROLYSIS OPERATION As liquid water is consumed within the URFC stack, water is pulled from the water storage tank. Gases exiting the URFC stack pass through condensers and dryers where the gas is dried to the dewpoint of the cold ambient environment. The oxygen flows either into the gas side of the water storage tank or through a check valve and into the oxygen storage tank. The hydrogen gas flows through a check valve and into the hydrogen storage tank. The pressure builds up in the URFC stack and in the storage tanks until electrolysis stops because either the solar power is no longer available or the storage tanks are fully charged. The storage tanks are sized so that as gas is stored and pressures rise, the hydrogen and oxygen pressures remain relatively equal inside the cell. Sufficient cold, ambient air is passed over the URFC stack to cool the stack and heat the air to above the freezing point. The warmed air provides the necessary environment for the condensers and other URFC components.

FUEL CELL OPERATION Reactants are withdrawn from the storage tanks through forward biased pressure regulators that maintain the oxygen and hydrogen pressures inside the cell stack. The reactants are humidified inside the regenerative dryers and condensers prior to entering the URFC stack. Product water formed during the reaction is absorbed into the water compartment in the URFC stack. The water is drawn into the water storage tank, which has a lower pressure than the gas compartments.

ELECTROLYSIS TO FUEL CELL TRANSITION The electrical load is applied to the cell circuit and current is drawn from the cell stack. The reactants are first drawn from the available reactant volume downstream of the pressure regulators. As these reactants are consumed, the pressure falls to the point where the gas starts flowing through the pressure regulators to maintain the pressure. The gas dryers become gas

humidifiers by allowing the water contained in the dryers to warm up and contact the dry gas flowing through. The condensers and the water compartment within the URFC stack supply additional humidification.

FUEL CELL TO ELECTROLYSIS TRANSITION The electrical load is disconnected from the cell circuit and power is applied to the cell stack. The generated gases flow through the condensers and dryers which now switch from humidifiers to dryers by cooling the gas flowing through and condensing/freezing the water vapor. The pressure upstream of the check valves builds up to the point where the pressure is greater than the pressure in the storage tanks. This allows the gas to flow through the check valves and into the storage tanks.

URFCS WEIGHT SUMMARY AND PACKAGING DESCRIPTION

Table 1 shows a tabulated list of components and their estimated weight for a URFCS capable of delivering 3500 watts during a 12 hour discharge period. Because of the simplicity of the URFCS there are very few components. Also, there are no rotating components. The overall energy density is 791 w-hr/kg, which is exceptionally light. It's expected that as the system design matures the overall weight will increase, but this initial analysis indicates the potential for an exceptionally lightweight energy storage system.

Table 1. URFCS Component List and Weights

Component	Wgt,k g	Performance Description
H2 @ discharge	0.1	1.4 kg/cm ² tank ancillary
O2 @ discharge	0.74	1.4 kg/cm ² tank ancillary
Water @ discharge	18.88	15.68 reactant, 3.2kg ancillary
URFC Stack	15.05	220 watt/kg, 139 cells, 136.6 cm ² per cell
H2 Storage Tank	6.28	0.598m ³ ,0.61m ID,1.63m L, 28 kg/cm ² MOP,1.5 SF
O2 Storage Tank	3.12	0.297m ³ ,0.61m ID,0.61m L, 28 kg/cm ² MOP,1.5 SF
Water Tank	2.27	
H2 Regulator	0.11	ancillary
O2 regulator	0.11	ancillary
Check Valves (2)	0.09	ancillary
H2/Water Condenser	0.11	ancillary
O2/Water Condenser	0.11	ancillary
H2 Regenerative Dryer	0.11	ancillary
O2 Regenerative Dryer	0.11	ancillary
Ducting	0.91	ancillary
Tubing	0.91	ancillary
Wiring	1.36	ancillary
Power Control	2.00	ancillary
System Control	0.68	ancillary
Total Weight,kg	53.06	
Energy, w-h	42000	3.5kw, 12hr/12hr charge/discharge
Energy Density,w-h/kg	791.56	

Figure 9. shows a conceptual packaging arrangement for the URFCS within a protective, aerodynamic shell. Air enters the leading end of the shell through louvers in the shell as a result of the forward speed of the aircraft. The cold air both cools the URFC stack and maintains the tanks at low temperature. The waste heat of the URFC stack warms the cold air to above the freezing point of water. Air exits from both the bottom and rear sides of the shell.

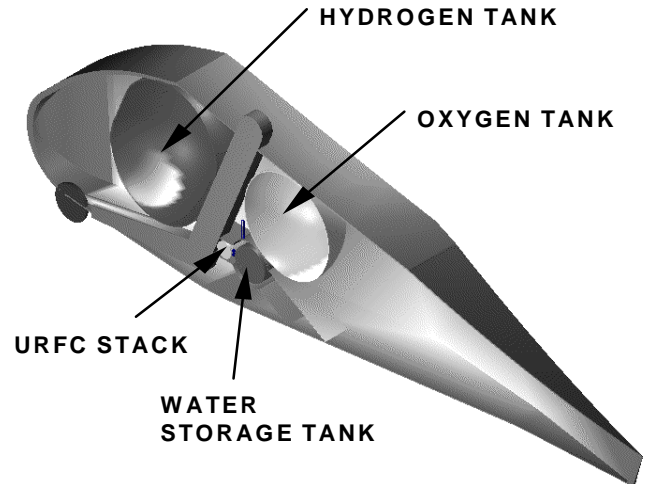


Figure 9. Packaging Concept for URFCS

URFCS PERFORMANCE

The system previously described was analytically modeled in a computer spreadsheet. A mass balance of the system was completed that allowed the masses of water (in gas, liquid, or solid states), as well as oxygen and hydrogen to be calculated for individual control volumes that made up the entire URFCS. The URFCS schematic identifying the network of individual control volumes is shown in Figure 10.

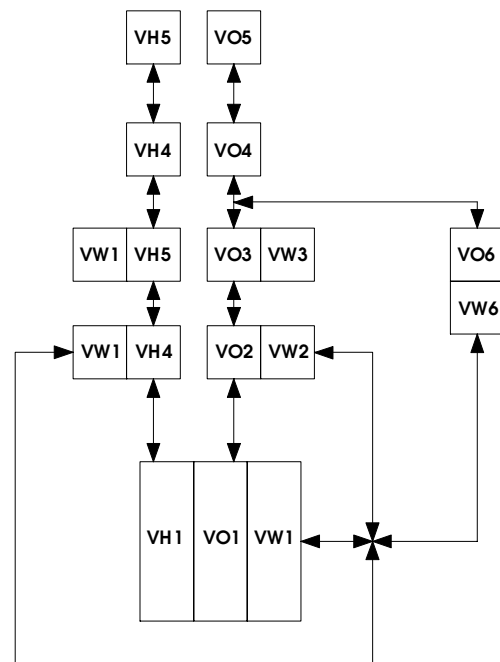


Figure 10. URFCS Control Volumes Model

The simulated control volumes were:

VO1-URFC Stack O2 Compartment
VO2-URFC O2 Condenser Vapor Compartment
VO3-URFC O2 Regen. Dryer Vapor Compartment
VO4-URFC O2 Post Dryer/Pre Regulator Compartment
VO5-URFC O2 Tank Storage Compartment
VO6-URFC H2O Tank Oxygen Reference Compartment
VH1-URFC Stack H2 Compartment
VH2-URFC H2 Condenser Vapor Compartment
VH3-URFC H2 Regen. Dryer Vapor Compartment
VH4-URFC H2 Post Dryer/Pre Regulator Compartment
VH5-URFC H2 Tank Storage Compartment
VW1-URFC Stack H2O Compartment
VW2-URFC O2 Condenser Liquid H2O Compartment
VW3-URFC O2 Regen. Dryer Ice Compartment
VW4-URFC H2 Condenser Liquid H2O Compartment
VW5-URFC H2 Regen. Dryer Ice Compartment
VW6-URFC H2O Tank Liquid Water Compartment

The water tank was sized to provide sufficient water storage for 3500 watts discharge power for 12 hours, plus 20% additional water to make up for gas and water loss from the system. The gas tank volumes were sized such that the fully charged tanks had a peak storage pressure of approximately 28.1 kg/cm² (400psia), and that the pressures remained approximately equal to each other during both the charge and discharge operation of the URFCs.

URFC STACK ELECTRICAL PERFORMANCE The unitized cell electrical performance was modeled according to the voltage versus current density curves shown in figure 11.

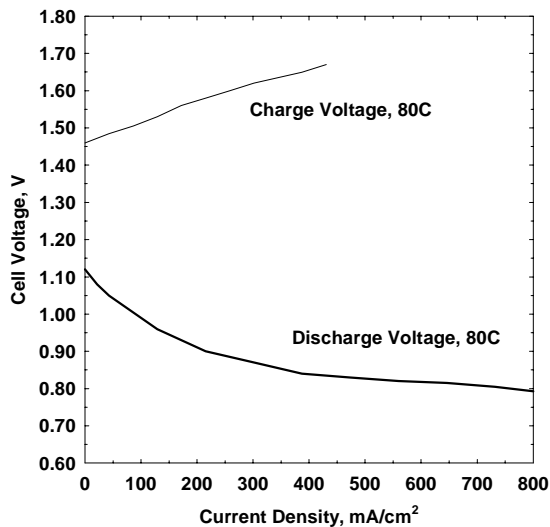


Figure 11. Cell Voltage vs. Current density

The cell performance data is for operation at 80C. This was the operating temperature during both charge and discharge. The operating temperature of the URFC stack was maintained at 80C by controlling the airflow into the inlet ductwork. Based on the power profile illustrated in figure 7, the operating current density and average cell voltage of the URFC stack were calculated for a 24-hour cycle in 5-minute increments. This is shown in Figure 12. The URFC stack is capable of instantaneous switching between charging and discharging

mode. The current density and cell voltage profiles reflect the shape of the power profile shown in Figure 7. The input power voltage is boosted to provide the needed charging voltage. The discharge voltage of the URFC stack is the same as the airplane bus voltage.

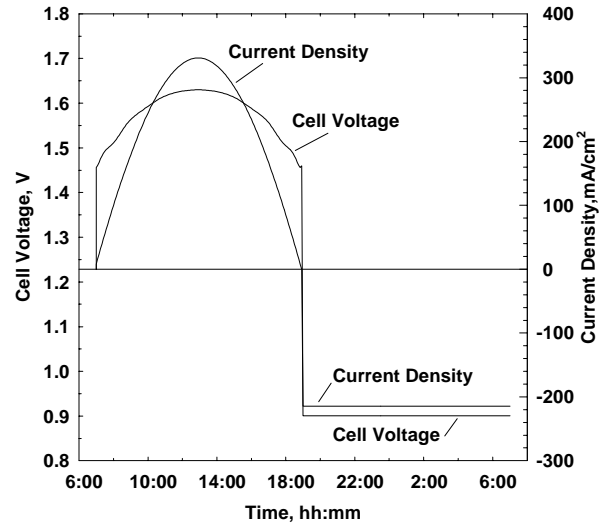


Figure 12. Cell Electrical Performance vs. Time

URFCS REACTANT MASS/PRESSURE The masses of the water (whether in gaseous, liquid, or solid form), oxygen, and hydrogen for each control volume as well as the mass rates entering and leaving each control volume were calculated for 5 minute time intervals. The partial pressures of hydrogen, oxygen, and water vapor were similarly calculated for each control volume containing a gaseous phase. Figure 13 shows the change in mass of water, hydrogen and oxygen during a 24-hour cycle. The tank storage pressure of both the hydrogen and oxygen are also shown in Figure 13. The conversion of the water to hydrogen and oxygen during the charging of the URFCS has the same sinusoidal profile as the power profile curve.

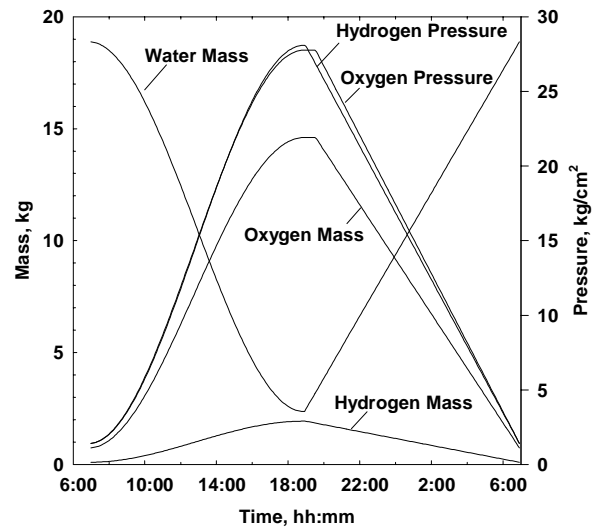


Figure 13. Reactant Mass/Pressure vs Time

The straight linear discharge portion of the curves in Figure 13 reflects the constant power level maintained during the night. The hydrogen tank and oxygen tanks were sized such that the pressures remained approximately equal to each other during

all portions of the cycle. The hydrogen pressure is slightly higher than the oxygen tank pressure because some of the stored oxygen is used to pressurize the water storage tank. The hydrogen tank starts to depressurize before the oxygen tank because after the initial switch to discharge operation, the oxygen in the water storage tank supplies the URFC stack. Until the pressure of this oxygen falls below the pressure set by the oxygen pressure regulator no oxygen is withdrawn from the oxygen tank. The volume of hydrogen between the hydrogen pressure regulator and the URFC stack is much smaller than the volume of oxygen between the oxygen pressure regulator and the URFC stack. Consequently the pressure of the hydrogen falls below the regulated value faster than the oxygen. To prevent a large pressure differential from building up during this initial discharge of the URFC stack, the hydrogen pressure regulator is referenced to the oxygen pressure. In this way, as the oxygen pressure more slowly declines to the level set by the oxygen pressure regulator, the hydrogen pressure “tracks” this pressure decline. Figure 14 shows the URFC stack hydrogen and oxygen pressure during the cycle. During the charging portion of the cycle the URFC stack pressures are very similar to the storage tank pressures. At the onset of the discharge portion, the gas on the downstream side of the regulators “bleeds” down until it reaches the regulated value. This “bleed-down” period is about 40 minutes, after which the URFC stack pressure is maintained at a constant level of about 1.4kg/cm^2 .

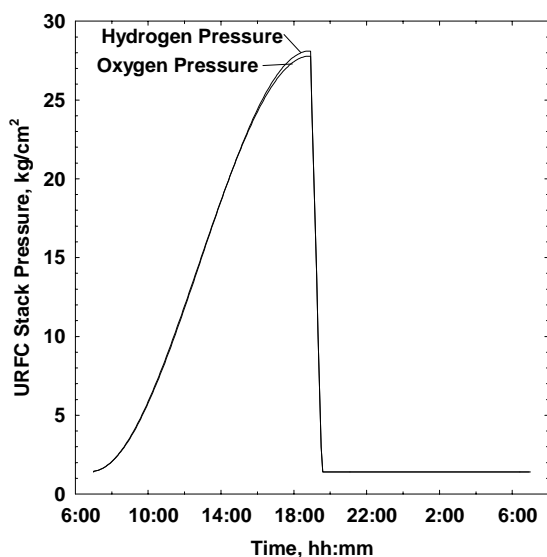


Figure 14. URFC Stack Pressure vs Time

WATER VAPOR MANAGEMENT The hydrogen and oxygen that exit the URFC stack during charging are saturated with water vapor at a dewpoint equal to the operating temperature of the URFC stack. This raises two issues. First, un-reacted water is being carried away from the reaction site, and should be returned so that water is used efficiently in the URFCs. Second, as stated earlier, it is highly desirable to store the hydrogen and oxygen at low temperature to minimize tank weight. Wet gas introduced to very cold tanks would cause the water vapor to freeze, trapping it in the storage tanks. To address both of these issues, the gases are dried in a two-stage process. Figure 15 shows the amounts of condensation in each of the two stages during the 24-hour cycle. The first stage

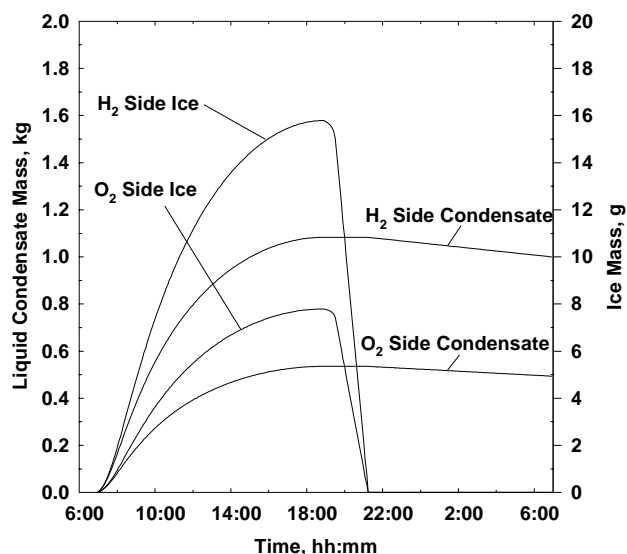


Figure 15. URFCs Water Vapor Management

condenses out most of the water (.5-1.0kg) within a 2-4C condenser. The second stage freezes the remaining water (8-16 g) within the regenerative dryers. This ice is recovered from the regenerative dryers by heating the dryer to above the freezing point. The moisture is carried back to the URFC stack by the dry gases as they pass through the regenerative dryers. The regenerating process occurs during the first two hours of the discharge cycle. Since the amount of ice is so small, the energy involved in melting the ice is also small. The change in water’s enthalpy from ice at 216K to a saturated vapor at 273K is approximately 0.8 w-h/g. In the case of the ice in the hydrogen regenerative dryer there is about 16g, so the energy to melt the ice and produce water vapor at 273K is about 12.8 w-h. A similar calculation for the ice in the oxygen regenerative dryer yields 6.4 w-h.

CONCLUSION

The energy density of a URFCs has the potential to be well in excess of battery-based energy storage systems. The longer the discharge time for the URFCs the greater the energy density possible. Energy densities as high as 800 w-h/kg are possible for URFCs based energy storage systems when the discharge time is 12 hours. With discharge times as short as 1 hour, the energy density of the URFCs still appears to have a weight advantage over battery-based energy storage systems. Terrestrial day/night cycles typically will have discharge times greater than 1 hour. For terrestrial applications where the weight of the energy storage system has a dominant effect on the success of an application, such as the solar-powered airplane, the URFCs might enable these applications.

The solar-powered airplane requirement of an ultralight energy storage system to enable “eternal” flight at altitudes of greater than 15,000m appears to be achievable. In fact, the analysis in this paper indicates that energy densities almost twice that needed may be achievable while maintaining the required energy efficiency. The lighter the energy storage system, the greater the payload the plane will be able to carry and sustain in flight.

The design of the URFCS presented in this paper incorporates a unique, passively operated URFC stack. This stack requires no pumps to supply it with reactants or cooling. The balance of the URFCS takes advantage of the operating environment of the solar-powered airplane to manage the water, hydrogen and oxygen, as well as the cooling of the cell stack and the thermal management of the other components of the URFCS. The passive pressure management of the water, hydrogen and oxygen utilizes only five components, which improves reliability while minimizing weight and ancillary power. A unique and innovative approach to drying of the hydrogen and oxygen provides a simple and lightweight solution to the problem of gas storage. By storing the gases dry and cold, gases could be stored in the unheated main structural member of the airplane's wing. With this approach, over 90% of the volume could be saved from the energy storage system described in this paper. A 18% weight savings would also be realized from the energy storage system. Additional structural weight from the airplane could be saved because the energy storage system would be 90% smaller and 18% lighter.

Although this paper primarily dealt with enabling the solar-powered airplane application, other weight-sensitive terrestrial and aerospace transportation and portable power applications may similarly be enabled.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

DOE Department of Energy

NASA National Aeronautics and Space Administration

PEM Proton Exchange Membrane

RFCS Regenerative Fuel Cell System

TRL Technology Readiness level

URFC Unitized Regenerative Fuel Cell

URFCS Unitized regenerative Fuel Cell System

A_c = Unit Cell Area, cm^2

A_t = Total Cell Area, cm^2

A_w = Dry Weight of URFCS Ancillaries, kg

gmole O_2 = Gram Moles of Oxygen Reacted

gmole H_2 = Gram Moles of Hydrogen Reacted

I_c = Average Charging Current, A

i_d = $f(V_d)$ = Discharge Current Density, A/cm^2

I_d = Average Discharge Current, A

K_a = $\frac{A_t}{S_w}$ The ratio of the total cell area to stack weight

K_w = $0.33 \times 10^6 \text{ cm}$ Water-Tank-Figure-of-Merit

MOP_G = Maximum Operating Gas Pressure, kg/cm^2

MOP_w = Max. Operating Pressure of Water Stored, kg/cm^2

M_w = mass of H_2 and O_2 that combined to form water, kg

η = Energy Efficiency = $\frac{\text{Output Energy}}{\text{Input Energy}}$

n = Number of Cells in the URFC Stack

n_c = Number of Cells Used During Charge

n_d = Number of Cells Used During Discharge

ρ = $.001 \text{ kg}/\text{cm}^3$ (the density of water)

R = Ideal Gas Constant $\frac{84.78 \text{ kg-cm}^3}{\text{cm}^2\text{-gmole-K}}$

S_w = Dry Weight of URFC Stack, kg

T = Temperature, K

t_c = Charge Time, hr

t_d = Discharge Time, hrs

T_w = Dry Weight of Gas Storage Tanks, kg

V_d = Discharge Cell Voltage, V

V_w = Volume of Water Stored, cm^3

W_w = Dry Weight of Water Storage Tank, kg

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